Accelerate Synthesis in Ecology and Environmental Sciences

STEPHEN R. CARPENTER, E. VIRGINIA ARMBRUST, PETER W. ARZBERGER, F. STUART CHAPIN III, JAMES J. ELSER, EDWARD J. HACKETT, ANTHONY R. IVES, PETER M. KAREIVA, MATHEW A. LEIBOLD, PER LUNDBERG, MARC MANGEL, NIRAV MERCHANT, WILLIAM W. MURDOCH, MARGARET A. PALMER, DEBRA P. C. PETERS, STEWARD T. A. PICKETT, KATHLEEN K. SMITH, DIANA H. WALL, AND ANN S. ZIMMERMAN

Ecology is a leading discipline in the synthesis of diverse knowledge. Ecologists have had considerable experience in bringing together diverse, multinational data sets, disciplines, and cultural perspectives to address a wide range of issues in basic and applied science. Now is the time to build on this foundation and invest in ecological synthesis through new national or international programs. While synthesis takes place through many mechanisms, including individual efforts, working groups, and research networks, centers are extraordinarily effective institutional settings for advancing synthesis projects.

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The synthesis of diverse knowledge is a central part of all sciences, especially those that draw information from many disciplines, such as ecology and environmental sciences. Research and education in ecology are intrinsically synthetic—solutions for environmental challenges increasingly require synthesis. Expansion of the already vast body of relevant knowledge makes synthesis ever more important. To accelerate pure and applied advances in ecology and environmental sciences, we see a pressing need for comprehensive new programs to energize synthesis. Synthesis and related activities, which often occur through sustained, intense interactions among individuals with ready access to raw data, metadata, and sophisticated analytical tools, make it possible to

- analyze disparate data sets and mine them from new perspectives that allow novel analyses;
- develop and use new analytical, computational, visualization, and modeling tools that may lead to greater insights;
- bring theoreticians, empiricists, modelers, and practitioners together to formulate new approaches to existing questions;
- and integrate science with education and real-world problems.

Synthesis occurs when disparate data, concepts, or theories are integrated in ways that yield new knowledge, insights, or explanations (Pickett et al. 2007). Synthesis creates emergent knowledge in which the whole is greater than the sum of the parts. By engaging experts with multiple perspectives, synthesis is capable of vetting a vast body of information for use by other disciplines or by society in general. Synthesis takes stock of what we know and generates new knowledge from novel combinations of existing information.

Teamwork speeds synthesis and thereby accelerates innovation. As the foundational knowledge of the sciences has grown, processes of innovation have changed. The "burden of knowledge" (Jones 2009) embedded in increasing numbers of journals, papers, and books requires synthesis, if problem solvers are to use that mass of information efficiently. Synthesis leapfrogs the linear and sequential progress of discovery by converting the serial steps into parallel, interacting ones. Trends in patents (Jones 2009) demonstrate the value of the process: In recent years, innovations leading to patents have been accomplished by older people who have had more time to process knowledge, in narrower specialties in which there is less relevant knowledge to consider, or, increasingly, by interdisciplinary teams that have used synthesis to integrate multiple areas of knowledge. Innovations of this latter kind can readily be accelerated by new institutions and funding mechanisms.

Synthesis is crucial for solving environmental problems and finding new, sustainable approaches for agriculture, energy, infrastructure, transportation, and other sectors. Assessments that synthesize environmental knowledge are increasingly employed for policy analysis (Miller 2009). The Inter-

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governmental Panel on Climate Change (*www.ipcc.ch/*), the Millennium Ecosystem Assessment (*www.millennium assessment.org*), and the Heinz Center's *State of the Nation's Ecosystems* reports (*www.heinzctr.org/ecosystems*) have distilled complex data into forms useful for policymakers. Assessments are limited more by a shortage of experts trained in synthesis to transcend discipline-bound perspectives than by a lack of deep knowledge from the contributing disciplines.

Skills in synthesis are as important as field or laboratory skills for the practicing scientist. Like other skills, synthesis must be taught and opportunities to practice synthesis must be created. This training is best done early in a scientist's career. Training in synthesis conveys the ability to condense the essential points from one's own discipline, work constructively with diverse experts, respect diverse ways of knowing and kinds of knowledge, recognize and distill pattern from complexity, and explain synthetic findings to policymakers and other stakeholders.

Moreover, synthesis creates teaching opportunities. Distributed graduate seminars, administered by the National Center for Ecological Analysis and Synthesis (NCEAS; *www.nceas.ucsb.edu*) of the National Science Foundation (NSF), can involve hundreds of graduate students in a synthesis activity (Andelman et al. 2004). Faculty from multiple universities choose a topic that could benefit from synthesis and go to the NCEAS to plan a graduate seminar that will run concurrently at their campuses. Students analyze and synthesize data under the guidance of participating faculty, and an NCEAS Web site allows collaboration among students and faculty in the simultaneous courses. Later, the faculty and two students from each campus come together at the NCEAS to complete the synthesis.

Cyberinfrastructure—a kind of information technology that brings together data, instruments, computational tools and services, and people—has coevolved in collaborative fashion with synthesis. Massive growth in cyberinfrastructure is needed to facilitate documentation, organization, preservation, and sharing of the rapidly expanding databases used in ecology and environmental science. Cyberinfrastructure tools enhance collaboration, enable synthesis among users at many locations, and support and deliver education and outreach. People too are part of cyberinfrastructure; those with computing expertise should be integral to synthesis teams.

Ecology has a significant head start in synthesis because the field has a long history of knowledge integration. Prescient investments in, for example, the NCEAS have established leadership in ecological and environmental synthesis. These successes have been emulated within the discipline of ecology in the Netherlands (*www.paralimes.org*), Sweden (*www.stockholmresilience.org*), Uruguay (*www.saras-institute.org*), and other countries. Similar NSF centers in other disciplines have also been inspired by the NCEAS. Opportunities to boost the power of synthesis through global networking of ecological and environmental synthesis centers are unprecedented.

Centers bring unique capabilities and create unmatched opportunities for synthesis. Social scientists who have studied the work of the NCEAS attribute its remarkable success to intense face-to-face interactions (Hackett et al. 2008). Processes such as "peer review on the fly" combine skepticism, instant criticism, and response, leading to very rapid modification of initial ideas and to conceptual advances. Centers offer isolation from distractions; provide neutral ground, leading to more openness and encouraging a greater diversity of participation; create new networks, connections, and unexpected synergies; concentrate infrastructure, which not only facilitates logistics and computing but also allows an intense focus on the science; and promotes consistency of expectations—participants come to expect, and hence work toward, fast progress on exciting questions. No other mechanism for synthesis presents these advantages.

Proven mechanisms for synthesis—individual efforts, working groups, and research networks, for example—can be supported in many ways. The NSF funds a number of synthesis activities, including those associated with centers, the Long Term Ecological Research network, new emerging networks, individual synthesis efforts, and other programs. We anticipate that rapid progress in observing platforms and self-organized networks of ecologists and field sites (Peters 2008) will create even more new synthesis opportunities.

Ecologists and scientists in closely connected disciplines in the biological, computational, atmospheric, hydrological, geological, oceanic, and social sciences need a national program of synthesis that accelerates discovery and research in basic and applied environmental science through interdisciplinary analysis and synthesis activities. The United States lacks a program specifically focused on environmental science synthesis, where ecology and multiple disciplines intersect. The need to coordinate synthesis across diverse mechanisms and disciplines calls for a new umbrella structure, a national or international program for environmental synthesis. Such a program should coordinate the various activities funded for synthesis (individual efforts, collaborative grants, networks, and centers); the interactions of ecology with the computational sciences, engineering, geosciences, paleosciences, and social sciences; and the networking of emerging synthesis activities around the world.

Ecology, a hybrid science with expanding boundaries, strives to answer core questions of crucial importance to humanity's future. Thus ecology has been a hotbed of scientific synthesis, and synthesis has been a driver of innovation. Now is the time to build on that foundation and further refine the best practices of synthesis within ecology. It is also time to spread the culture of synthesis more extensively to undergraduate and postgraduate education, across the basic-to-applied spectrum toward management and governance, and beyond disciplinary boundaries into sciences allied with ecology. We must continue and accelerate the trend to share data and credit for collaborative work, and to recognize individuals who make generous contributions to collaborative science. The whole academic community, from individual research projects to hiring and promotion processes, must change to embrace synthetic perspectives. We need fewer incentives for narrow papers and projects, and more resources for working toward the horizon. Organizations that fund research are in the key position to foster this spread of the culture and practice of synthesis and to stimulate new synthesis, which will benefit science and society.

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Stephen R. Carpenter (srcarpen@wisc.edu) is with the Center for Limnology, and Anthony R. Ives is with the Department of Zoology, at the University of Wisconsin in Madison. E. Virginia Armbrust is with the Center for Environmental Genomics at the University of Washington in Seattle. Peter W. Arzberger is with the National Biomedical Computation Resource, University of California, San Diego. F. Stuart Chapin III is with the Department of Biology and Wildlife at the Institute of Arctic Biology, University of Alaska, Fairbanks. James J. Elser is with the School of Life Sciences, and Edward J. Hackett is with the Center for Nanotechnology in Society, at Arizona State University, Tempe. Peter M. Kareiva is with the Nature Conservancy in Seattle, Washington. Mathew A. Leibold is with the School of Biological Sciences, Section of Integrative Biology, at the University of Texas in Austin. Per Lundberg is with the Department of Theoretical Ecology at Lund University, Sweden. Marc Mangel is with the Department of Applied Mathematics and Statistics at the Jack Baskin School of Engineering, University of California, Santa Cruz. Nirav Merchant is with Biotechnology Computing at the University of Arizona in Tucson. William W. Murdoch is with the Department of Biological Sciences at the University of California, Santa Barbara. Margaret A. Palmer is with the Chesapeake Biological Laboratory at the University of Maryland Center for Environmental Sciences in Solomons. Debra P. C. Peters is with the US Department of Agriculture Jornada Experimental Range in Las Cruces, New Mexico. Steward T. A. Pickett is with the Cary Institute of Ecosystem Studies in Millbrook, New York. Kathleen K. Smith is with the Department of Biology at Duke University in Durham, North Carolina. Diana H. Wall is with the Natural Resource Ecology Lab at Colorado State University in Fort Collins. Ann S. Zimmerman is with the School of Information at the University of Michigan, Ann Arbor.